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AD A107312

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TECHNICAL REPORT ARBRL-TR-02373

SECONDARY COMBUSTION IN GUN EXHAUST FLOWS

Edward M. Schmidt

October 1981

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TECHNICAL REPORT ARBRL-TR-02373	2. GOVT ACCESSION NO. AD-A107312	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SECONDARY COMBUSTION IN GUN EXHAUST FLOWS		5. TYPE OF REPORT & PERIOD COVERED Final rept.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Edward M. Schmidt		8. CONTRACT OR GRANT NUMBER(s) 16
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Ballistic Research Laboratory (ATTN: DRDAR-BLL) Aberdeen Proving Ground, MD 21005		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS RDT&E 1L161102AH43
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Armament Research & Development Command US Army Ballistic Research Laboratory (ATTN: DRDAR-BL) Aberdeen Proving Ground, MD 21005		12. REPORT DATE ~~October 1981~~ Oct 81 13. NUMBER OF PAGES 39
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 12 37		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Secondary Combustion
Muzzle Flash
Ignition
Transient Flow

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (ner/ems)

The muzzle flash from cannon is analyzed using a simple description of the gun exhaust plume flow structure coupled to an empirical ignition criteria. The effect of muzzle devices such as recoil brakes is estimated through an approximate description of their internal flow. The influence of the transient nature of the weapon exhaust plume is examined by using a one-dimensional, unsteady numerical model to develop the flow properties along the axis of symmetry. These properties are input into the ignition model and the possibility of the occurrence of secondary combustion is determined (continued)

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as a function of time during gun tube emptying.

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1. INTRODUCTION

Excessive blast overpressure in the crew area of artillery pieces is restricting the operation of certain current systems. One reason for the emergence of the problem with newer cannon is the requirement to increase weapon performance, generally through the use of highly energetic propellants. These produce high pressure and temperature in the gases exhausting from the weapon muzzle following shot ejection. As a result the blast overpressure due to the expanding gases increases. Additionally, the propensity of the exhaust plume to ignite into secondary combustion of the unoxidized propellant gas species increases. Secondary combustion results in excessive flash signature of the weapon improving probability of detection and reducing night vision of the artillery crew. Another, equally serious effect of this combustion is the generation of strong pressure disturbances which can reinforce the initial blast pulse and lead to excessive overpressure in the vicinity of the crew member. In the present report, muzzle flash is described and an attempt to analyze some of the features of the phenomena using relatively simple methodology is presented.

The development of the flow from the muzzle of a gun has been extensively investigated for the bare muzzle configuration[1-4]. The structure (Figure 1) consists of two impulsive jets. The first, or precursor, develops as the air in the gun tube is forced out ahead of the projectile. The second, propellant-gas, jet develops when these high pressure gases are released by projectile separation. The muzzle pressure level of the precursor jet is typically an order of magnitude lower than that in the propellant gases. As such, this initial flow is rapidly engulfed in the expanding propellant gas jet and associated air blast. The propellant gas plume growth is influenced by the precursor flow, the projectile, and the ambient conditions. However, the gross nature of the plume development is highly directional[3]. The Mach disc moves continuously away from the muzzle leaving behind a lateral shock structure which is essentially invariant once established. This is contrary to the decay of the plume wherein the total jet structure shrinks toward the muzzle.

The behavior of the Mach disc is of particular importance since the shock heating of the propellant gases strongly influences the occurrence of secondary

1. *J. Erdos and P. DelGuidice, "Calculation of Muzzle Blast Flowfields," AIAA Journal, Vol. 13, No. 8, August 1975, pp. 1048-1058.*

2. *G. Moretti, "Muzzle Blast Flow and Related Problems," AIAA Paper No. 78-1190, AIAA Fluid and Plasma Dynamics Conference, Seattle, July 1978.*

3. *E. Schmidt and D. Shear, "Optical Measurements of Muzzle Blast," AIAA Journal, Vol. 13, No. 8, August 1975, pp. 1086-1091.*

4. *T. Taylor and T. Lin, "A Numerical Model for Muzzle Blast Flow Fields," AIAA Journal, Vol. 19, No. 3, March 1981, pp. 346-349.*

combustion. From optical measurements it is observed that at early times, the Mach disc dominates the flow. Almost all of the exhausting gases are processed through it. At later times when the plume has grown to its maximum dimensions, the Mach disc attains its greatest strength but only processes a small fraction of the exhaust flow (10-15%). During this period of rapid changes in the flow structure, the muzzle exit conditions are continuously decaying. Thus, the properties of the exhaust gases which mix with the surrounding air in the lateral viscous layers, impulsive vortex, and turbulent jet are spatially and temporally non-uniform.

Cannon flash is related to the development of these jet flowfields (Figure 2). As the projectile accelerates down the gun tube, high pressure propellant gases leak around it and mix with the tube gas. If this gas was largely air, the ejected mixture could be burning upon exit; or, if the tube gas was mainly the propellant gases remaining from a previously fired round, then mixture with the atmosphere could cause ignition. In any case, the flash which can occur prior to the round breaking the muzzle is known as *preflash*. With uncorking of the projectile, the propellant gases are released. At the muzzle, the propellant gases are at a high temperature and particulates in the flow incandesce. This bright orange glow is known as *primary flash*. As the gases move away from the muzzle, the strong expansion within the supersonic core of the jet quenches this incandescence. When the gases pass the Mach disc, the temperature rises toward the stagnation value (in excess of the muzzle temperature) and strong luminosity may once more be observed. This region is termed *intermediate flash*. By far the most severe flash phenomena is *secondary flash* resulting from the combustion of the propellant gas/air mixture at the boundary to the impulsive jet. The propellant gases mix with air in the turbulent shear layer on the lateral jet boundary and in the vortex ring which entrains flow which passes the Mach disc. Since the propellant gases are not fully oxidized, mixture with air can develop a combustible mixture requiring only a suitable source of ignition. Some possible sources of ignition include; preflash, burning powder particles, hot muzzle for burst fire, tracer rounds, or, more likely, ignition due to elevated temperatures in the gases behind the Mach disc and in the lateral shear layers.

The presence of muzzle devices can alter the flash characteristics of a particular weapon. Flash suppressors consist of conical or slotted nozzles which are placed on the muzzle of guns. These devices alter the shock structure in the exhaust plume preventing the formation of a strong normal shock in the plume and thereby reducing the temperature in the propellant gases. On the other hand, muzzle brakes can act as flash inducers. These devices consist of a series of baffles placed in the exhaust gases in order to deflect the flow and recover momentum for the attenuation of the recoil impulse. However, shock formation on baffle surfaces can cause severe heating of the exhaust gases. This is illustrated by examining the flash from a 30mm cannon (Figure 3). With no muzzle attachments, only minor luminosity is recorded on the photograph (color Polaroid film, ASA 75, f2.5). With a single baffle muzzle brake installed, the luminosity increases in the form of intermediate flash. With a double baffle muzzle brake installed, secondary flash completely envelops the exhaust field.

The energy released by secondary combustion of the propellant gases in the exhaust plume of guns can result in the generation of blast waves which

may be as strong as or stronger than the primary blast due to initial free expansion of the jet. Additionally, the secondary combustion induced blast may interact with the primary blast in a manner that significantly raises the overpressure level at a given position. For example, consider the blast field about a 155mm, M109 self-propelled howitzer firing a Zone 7 charge. From high speed photography, it was determined that in one of the firings, the weapon flashed; while in the second case no flash was observed. The pressure transducers were located along a 90° radial at a distance of 9.1 m from the weapon (Figure 4).

For the round where no flash was observed, the peak overpressure was 0.15 atmospheres and correspond to the arrival of the ground reflection at the gage station. For the round with flash, the peak overpressure is 0.24 atmospheres and corresponds to the arrival of a strong secondary pulse roughly coincidental with the ground reflection. In both cases, the free field blast due to the expansion of the muzzle gases has an identical level of 0.14 atmospheres. Similar alterations of the blast pulse due to the occurrence of muzzle flash have been observed in a number of other weapons. For the 81mm mortar, the problem was quite critical in that flash related overpressures two to three times greater than the expansion driven blast were recorded. In order to be capable of anticipating such problems, a means of predicting the probability of a particular weapon/projectile/propellant combination to produce secondary flash is desirable.

II. FLASH PREDICTION TECHNIQUE

A. Previous Approximations

The approach taken is to adapt existing techniques to approximate the gasdynamic processes occurring during the transient mixing of the exhausting propellant gases with the ambient. A significant amount of research has been dedicated to modeling the steady exhaust plume from rockets and has led to the development of standardized models of the flow, combustion, and radiation processes in these plumes[5,6]. However, these models are formulated to treat steady, axisymmetric flows from nozzles having relatively low exit pressure ratios. The exhaust from large caliber artillery firing high zone charges can leave the muzzle with pressures of 500 atmospheres or more. Additionally, the flow is transient and often three-dimensional. Attempts to estimate the ignition and combustion in such a flow require the application of significant simplifying assumptions.

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5. *S. M. Dash and H. S. Pergament, "The JANNAF Standard Plume Flowfield Model: Operational Features and Preliminary Assessment," JANNAF 12th Plume Technology Meeting, Colorado Springs, CO, 18-20 November 1980.*

6. *C. Ludwig, "Standard Infra-Red Radiation Model," JANNAF Plume Flow Field/ Radiation Workshop, Redstone Arsenal, AL, 2-3 April 1981.*

Carfagno[7,8] conducted extensive experimental investigations into the occurrence of and radiation from gun muzzle flash. He developed a set of ignition temperature limits for various mixtures of air and propellant gas at atmospheric pressure. The limits were established in shock tube tests. Combustion gas composition was determined from equilibrium calculations of the chemistry. Five propellants were simulated. Each had combustion products containing between 40 and 70 percent of combustible CO and H_2. Muzzle gas mixtures were simulated from commercial bottled gas and then mixed with air and water vapor. The mixture was placed in a shock tube and subjected to the incident and reflected waves in order to achieve the required pressure (atmospheric) and temperature. Ignition was determined from luminosity measurements.

From these tests, the ignition temperatures shown in Figure 5 were established. Carfagno found that there was relatively little variation with propellant composition; although, the addition of flash suppressants such as K_2SO_4 did raise the ignition temperatures measurably. After concentrations of 3% suppressant, little additional benefit was achieved.

Using these ignition temperature limits, Carfagno[8] examined the structure of the muzzle flow field. Through one-dimensional mixing and gasdynamic models, he attempted to characterize the flow processes that led to ignition. His recommended model (Figure 6) assumed that the propellant gas expanded isentropically to atmospheric pressure, mixed with the ambient, passed through a normal shock, re-expanded to atmospheric pressure, and finally was ignited if the mixture temperature exceeded the specified limits (Figure 5).

May and Einstein[9] point out that the flow model recommended by Carfagno is not in good agreement with experiment. Only the propellant gas passes through the normal shock (Mach disc) in the exhaust plume (Figure 1). They recommend an alternative approach (Figure 7). The propellant gas expands isentropically to atmospheric pressure, passes through a normal shock and re-expands to atmospheric pressure where mixing with air occurs followed by possible ignition. May and Einstein also use an improved interior ballistic model[10] to arrive at the weapon exit conditions.

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7. *G. Carfagno, Spectral Characteristics of Muzzle Flash, AMC Pamphlet 706-255, Army Materiel Command, Washington, D.C., June 1967.*

8. *S. Carfagno, Handbook on Gun Flash, The Franklin Institute, Philadelphia, PA, 1961.*

9. *I. May and S. Einstein, "Prediction of Gun Muzzle Flash," ARBRL TR 02229, U. S. Army Ballistic Research Laboratory, APG, MD, March 1980. AD A083888.*

10. *P. G. Baer and J. M. Frankle, "The Simulation of Interior Ballistic Performance of Guns by Digital Computer Program," BRL R 1183, U. S. Army Ballistic Research Laboratory, APG, MD, December 1962. AD 299980.*

properties are subsonic. The jet plume is approximated as steady[12] with the shock structure and mixing of the propellant gas streams processed through the lateral shocks and Mach disc according to Yousefian[11]. The mixing of the propellant gas and air occurs in an instantaneous, one-dimensional fashion using the approach of May and Einstein[9]. Finally, the Carfagno[8] ignition temperature criteria is applied.

To account for the unsteady development of the flow, the decay of the muzzle properties is computed in an approximate manner and coupled with both experimental[3] and numerical[1] descriptions of the growth and decay of the propellant gas plume and associated air blast. However, the basic application will assume quasi-steady conditions with muzzle exit conditions at the initial sonic value. A step-wise procedure is summarized below:

1. Compute weapon exit properties using a suitable interior ballistic analysis: (u_e, a_e, p_e)

2. Compute sonic conditions following projectile separation:

$$u^*/a_e = \frac{2}{\gamma+1} + \frac{\gamma-1}{\gamma+1}\,\frac{u_e}{a_e} \tag{5}$$

$$p^*/p_e = \left[\frac{u^*}{a_e}\right]^{2\gamma/(\gamma-1)} \tag{6}$$

$$T^* = u^{*2}/(\gamma R) \tag{7}$$

$$T_s^* = \frac{\gamma+1}{2}\,T^* \tag{8}$$

3. Isentropic expansion through lateral shocks to atmospheric pressure:

$$T_i = T^*\,(p_\infty/p^*)^{(\gamma-1)/\gamma} \tag{9}$$

$$u_i = [(T_s^* - T_i)/(2\,c_{p_e})] \tag{10}$$

4. Flow properties following transit of Mach disc may be estimated once Mach disc is located, Equation (1), and the Mach number of the flow entering the Mach disc, M_1, is determined, Equation (3). The properties of interest are:

$$p_2/p_\infty = [(2\gamma M_1^2 - (\gamma-1))/(\gamma+1)]\;[(\gamma+1)/(2 + (\gamma-1)M_1^2)]^{\gamma/(\gamma-1)}\,(p^*/p_\infty) \tag{11}$$

$$M_2 = [((\gamma-1)M_1^2 + 2)/(2\gamma M_1^2 - (\gamma-1))]^{1/2} \tag{12}$$

$$T_2 = T_s^*/(1 + \frac{\gamma-1}{2}M_2^2) \tag{13}$$

In general, the steady state location of the Mach disc should be such that $p_2 p_\infty \doteq 1.0$; however, if this is not the case, the flow will be assumed to

While the models of Carfagno and May and Einstein agree qualitatively with experiment, the approximations of the basic propellant plume flowfield are not satisfactory. Yousefian[11] uses a more realistic model of the supersonic jet as input to a finite difference computation of two-dimensional plume mixing and chemistry (Figure 8). He uses empirical correlations[12,13] to locate the downrange position and lateral extent of the Mach disc:

$$X_{m.d.}/D = 0.69\ (\gamma p^*/p_\infty)^{\frac{1}{2}}\ , \tag{1}$$

$$d_{m.d.}/D = 0.49\ (\gamma p^*/p_\infty)^{\frac{1}{2}}. \tag{2}$$

From computations of the supersonic core flow[12], Yousefian develops an expression which may be used to interpolate for the Mach number upstream of the Mach disc:

$$(X_{m.d.}/D)^2 = 0.49\ \gamma[2+(\gamma-1)M^2]^{\gamma/\gamma-1}[\gamma+1]^{-\frac{1}{\gamma-1}}\ /\ [2\gamma M^2 - (\gamma-1)] \tag{3}$$

Yousefian assumes that the only shock heating of importance occurs in the gas passing the Mach disc. Lateral shocks are taken to be sufficiently weak that isentropic expansion from muzzle conditions may be assumed. The fraction of propellant gas passing the Mach disc is given as

$$\alpha = 0.52\ (X_{m.d.}/D)^2\ M\ [(\gamma+1)/(2+(\gamma-1)M^2)]^{(\gamma+1)/2(\gamma-1)} \tag{4}$$

The two propellant gas streams are assumed to undergo instantaneous, one-dimensional mixing and form the input to a steady, two-dimensional finite difference computation of mixing and chemistry between the propellant gas and air.

While providing the most realistic model of muzzle flash to date, Yousefian fails to examine the influence of the basic unsteady nature of gun exhaust flow and does not treat the effect of muzzle devices common to large caliber gun systems. To examine these factors, a flash model is suggested which combines many of the features of the above approximations.

B. Present Model

The present model is illustrated schematically in Figure 9. To determine weapon exit conditions, the Baer and Frankle[10] interior ballistic model is applied. The expansion to sonic conditions is computed if the initial exit

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11. *V. Yousefian, "Muzzle Flash Onset," Aerodyne Research, Inc., Bedford, MA, ARI-RR-162.1, May 1979.*

12. *A. R. Vick, et al, "Comparison of Free Jet Boundaries with Theoretical Results Obtained with the Method of Characteristics," NASA TN D-2327, June 1964.*

13. *G. Keller, Private Communication, Ballistic Research Laboratory, APG, MD, July 1980.*

undergo isentropic expansion to ambient conditions:

$$T_{\delta} = T_2 \; (p_{\infty}/p_2)^{(\gamma-1)/\gamma} \tag{14}$$

$$u_{\delta} = [(T_s^* - T_{\delta})/2c_{p_e}] \tag{15}$$

5. The ratio of propellant gases passing the Mach disc is given by*:

$$\alpha = 0.96 \; (X_{m.d.}/D)^2 \; M_1[(\gamma+1)/(2+(\gamma-1)M_1^2)]^{(\gamma+1)/2(\gamma-1)} \tag{16}$$

6. Compute mixing of propellant gas streams:

$$\bar{u} = (1-\alpha) \; u_i + \alpha u_{\delta}$$

$$\bar{T}_s = T_s^*$$

7. Compute mixing of propellant gas with air:

$$\bar{\bar{c}}_p = rc_{p_\infty} + (1-r) \; c_{p_e}$$

$$\bar{\bar{u}} = (1-r) \; \bar{u}$$

$$\bar{\bar{T}}_s = [rc_{p_\infty} \; T_{s_\infty} + (1-r) \; c_{p_e} \; \bar{T}_s]/\bar{\bar{c}}_p$$

$$\bar{\bar{T}} = \bar{\bar{T}}_s - \bar{\bar{u}}^2/2 \; \bar{\bar{c}}_p$$

8. Compute the variation of the final temperature, $\bar{\bar{T}}$, versus mixture ratio and compare with the ignition limits specified by Carfagno (Figure 5).

III. 155MM HOWITZER FLASH

The 155mm, M109A1, self-propelled howitzer is used to examine the capabilities of the proposed flash prediction methodology. The weapon is equipped with a high efficiency muzzle brake (Figure 10). Firings of a 46kg, M483 projectile were conducted for Zones 3-8S. These data are supplemented by firings at Zone 8S with no muzzle brake attached to the tube. The latter firings were conducted by the Interior Ballistics Division, BRL, on a test stand.

**As described in following section, the coefficient is increased from that given by Yousefian to account for measured shock structure of actual muzzle flow.*

Both blast field pressure measurements and high speed cinematography were taken for each firing event. The high speed cinematography was accomplished with 16mm Fastax cameras framing at 2000 frames/s. Occurrence of secondary flash was quite evident in these photographs.

Launch properties were computed by Keller[13] and are summarized in Table I. The Zone 8S firings are of particular interest since this is the "super charge" configuration for the system. The thermodynamic properties for the M30A1 propellant which makes up this charge are:

$$\gamma = 1.24$$

$$T_a = 3012 \ {}^\circ K$$

$$c_p = 1849 \ m^2/S^2 \ {}^\circ K$$

$$R = 357.9 \ m^2/S^2 \ {}^\circ K$$

As previously mentioned, the M109A1 is equipped with a double-baffle muzzle brake. The presence of a baffle has been shown[14] to generate strong shock waves in the flow. To approximate the heating associated with the shocks standing off the baffle surfaces, the gasdynamic model shown in Figure 11 is employed. An axisymmetric plume expands from the muzzle and passes a normal shock at the first baffle. The shocked gas exits laterally as a plate jet and axially through the projectile hole. The gas passing the projectile hole reaches sonic velocity and forms a second plume which impinges upon the next baffle. After repeating the shock/expansion process on the second baffle, the flow expands as a free jet through the exit hole of the brake. This final exit flow is analyzed using the techniques described in the previous section.

For a Zone 8S firing, the mixture temperature is computed at various air/fuel ratios for both the bare muzzle and muzzle brake cases (Figure 12). The difference between the two temperature profiles is dramatic. With a bare muzzle, ignition is not predicted to occur; however, with the muzzle brake in place, mixture temperatures reach quite high values and ignition would be expected. Experiment shows that for Zone 8S with the muzzle brake in place, secondary combustion occurs in each of 20 observations. For the bare muzzle firings, the picture is not as clear. When the Zone 8S firings were conducted with the standard charge, secondary flash was not observed (one round); however, when 0.23kg of propellant was removed, secondary flash was observed (five rounds). Additionally, when the amount of flash suppressant was reduced to 1%, flash was observed (five rounds). In order to resolve this disagreement and to expand the bare muzzle data base, more firings are required.

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*14. *E. M. Schmidt, E. J. Gion and K. S. Fansler, "Measurement of Muzzle Blast and Its Impingement Upon Surfaces," AIAA Fluid and Plasma Dynamics Conference, Williamsburg, VA, AIAA Paper No. 79-1560, July 1979.*

Table I. 155mm, M109A1 Launch Properties

Zone	Propellant (kg/type)	%Suppressant	V_e (m/s)	T_e (°K)	a_e (m/s)	p_e/p_∞	u* (m/s)	p^*/p_∞	T_s^* (°K)
3	1.50/M1(SP)	2.0	250	1418	793	68	733	31.4	1319
5	3.21/M1(7P)	2.0	379	1425	795	148	749	82.6	1376
7	6.07/M1(7P)	1.5	542	1353	775	273	749	192.9	1376
8	9.59/M6(MP)	3.6	649	1490	813	486	795	393.1	1549
8S	12.24/M30(MP)	4.7	790	1756	883	703	872	629.5	1865

The prediction procedure was used for the remainder of the M109A1 tests conducted with the muzzle brake in place, Figure 13. The results are summarized in Table II.

Table II. 155mm, M109A1 Secondary Flash

Zone	Measured Secondary Flash	Predicted Secondary Flash
3	No	No
5	No	No
7	Yes	Yes
8	Yes	(?)
8S	Yes	Yes

The firings at Zone 7 showed two types of flash behavior. In some instances, secondary flash was observed only in the gas exiting through the projectile hole but not that passing out of the lateral vents. On other occasions, secondary combustion completely enveloped the field.

For the Zone 8 firings, the mixture temperature was predicted to be 70°K below the ignition limit. The observations showed combustion only in the gases exiting the projectile hole. With this charge, suppressant is added in the form of a 0.34kg bag of K_2SO_4 tied to the front of the charge (ammunition for the 155mm is separate loaded). There is some debate as to the nature of suppressant mixing with the propellant gases; thus, if the effective percentage of suppressant is lower, the mixture temperature could exceed the ignition limit.

Since the muzzle exhaust process is basically an unsteady phenomena, it is of interest to examine the sensitivity of muzzle flash predictions to changes in the nature of the flow.

IV. UNSTEADY FLASH ANALYSIS: BARE MUZZLE 155MM HOWITZER

The development of the muzzle flow field is illustrated in Figure 1. The shock structure within the propellant gas plume grows in a manner which is strongly influenced by the projectile presence and pressure field associated with the expanding air blast. Both medium caliber[14] and small caliber[3] weapons show nearly identical flow field properties at correctly scaled times if the exit conditions are similar in each case. The assumption that the inviscid flow structure for a 155mm howitzer can be scaled from data acquired on a 5.56mm rifle[3] will permit estimation of the influence of muzzle flo. field growth and decay.

The technique[10] used by Keller[13] to calculate weapon exit conditions can not define the temporal decay of propellant gas properties during tube emptying. For the 155mm, M109A1 firing the Zone 8S charge, this decay is estimated using data acquired from a 20mm cannon[14]. It is assumed that the property decay from peak values occurs similarly for both weapons if the time scale is

$$\bar{t} = t/\tau$$

where

$$\tau = L/a_o^*$$

L = gun tube length

a_o^* = initial sonic velocity in propellant gas at muzzle

For the 20mm case, only exit pressure could be measured. Lacking additional data, the remaining gas properties were estimated under the assumption that the emptying process was isentropic. For the 155mm howitzer, these approximations lead to the following:

Table III. 155mm, M109A1 Muzzle Exit Property Variation when Firing Zone 8S Charge

t (ms)	u^* (m/s)	p^*/p_∞	T^*_s (°K)
0	872	630	1918
1.9	835	446	1759
3.7	808	316	1647
5.6	784	234	1551
7.4	762	179	1469
9.3	741	134	1385
11.1	723	106	1319
14.8	692	67	1208
20.4	660	42	1099
26.0	626	25	989
30.0	594	15	890

The flow development was computed using a one-dimensional, unsteady numerical model developed by Erdos and DelGuidice[1] (Figure 14). It is interesting to note that by the time the propellant gas plume reaches its maximum size ($t \doteq 6$ ms), the muzzle exit conditions have dropped markedly from the initial levels. Five points were selected as representative of various stages of development. Two of the conditions were taken during growth of the plume; the fully developed stage was selected; and two conditions representing plume decay were examined.

From spark shadowgraph records of small caliber firings[3], the shock structure internal to the plume at each condition is determined (Figure 15). The following properties were determined:

Table IV. Mach Disc Properties During Growth and Decay of Propellant Gas Plume

Stage	t (ms)	$X_{m.d.}/d$	α	$V_{m.d.}$ (m/s)	$M_{1\,rel.}$
1	1	6.0	.99	698	3.7
2	3	12.3	.28	328	6.2
3	6	15.3	.16	0	7.7
4	9	12.5	.06	-255	8.2
5	15	6.5	.10	- 87	5.8

Using the computed Mach disc velocity, a relative flow Mach number is determined. Using this, the shock jump conditions are evaluated. The flash analysis described previously is then directly applied. For each stage of the flow life cycle, the mixture temperature variations are shown in Figure 16.

The most interesting feature of this plot is the prediction that the gas processed through the shock early in the development cycle, stage 1, produces very high mixture temperatures with an increased probability of ignition. This stage shows that very high fractions of the exhausting propellant gas are passing the Mach disc. Even though the wave is relatively weak, the mixture temperatures are significantly elevated.

As the growth of the plume continues, the mixture temperatures monotonically decay. Apparently, this portion of the cycle is dominated by the variation in muzzle exit properties and by the diminishing mass flow through the Mach disc.

The results of this analysis could help explain some of the bare muzzle firing data with the 155mm howitzer. Assuming the prediction of high mixture temperature propellant gases exiting at early times is correct, the Zone 8S charge would be borderline for even bare muzzle firings. Additionally, these results are partially supported by experimental results of Klingenberg and Mach[15] who show time-resolved, smear photographs of the muzzle flash from a 7.62mm rifle. Their data indicates combustion initiates behind the Mach disc in the gases which exit early in the tube emptying cycle. Additionally, the high speed cinematography of the 155mm shows a tendency for the propellant gas to ignite early in the venting. This initial secondary combustion may be extinguished as the fuel is consumed only to reignite later in the exhaust cycle.

V. SUMMARY AND CONCLUSIONS

The muzzle flow field from guns is analyzed to determine features which influence the tendency of the weapon to produce secondary flash. The gun tube exit conditions and plume shock structure are strong factors in the flash process. The presence of muzzle devices also is shown to alter the properties of the exhaust flow. Finally, the basic unsteady nature of the process appears to require serious consideration.

The model used in the analysis is overly simplistic. It does not treat the gasdynamics or chemical kinetics of the process in a satisfactory manner. However, the ignition criteria can be easily coupled to existing inviscid analyses of muzzle flow and used to point out qualitative variations in flash processes.

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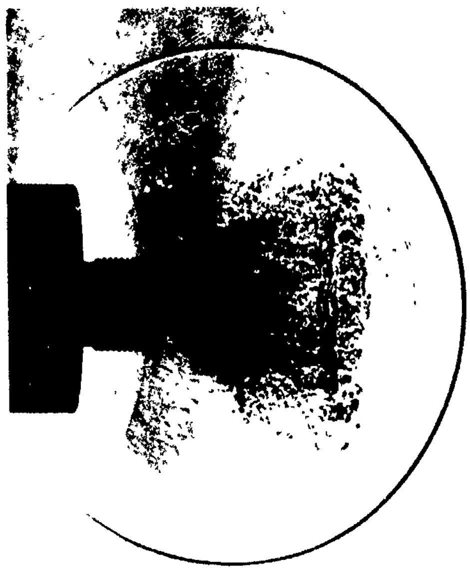
15. *G. Klingenberg and H. Mach, "Investigation of Combustion Phenomena Associated with the Flow of Hot Propellant Gases," Combustion and Flame, Vol. 27, 1976, pp 163-176.*

Additional experimental data is required to define the temporal sequence of muzzle flow ignition and combustion. Improved analytical techniques are needed to address the problem of transient, high pressure exhaust flows.

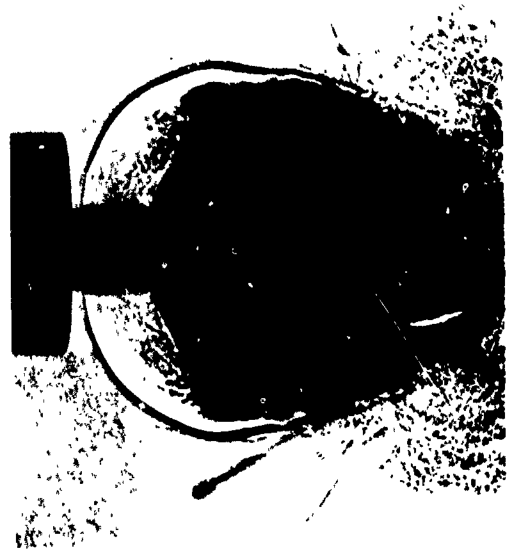
VI. ACKNOWLEDGMENT

The author wishes to thank Drs. K. Fansler and G. Keller for many useful suggestions and essential inputs.



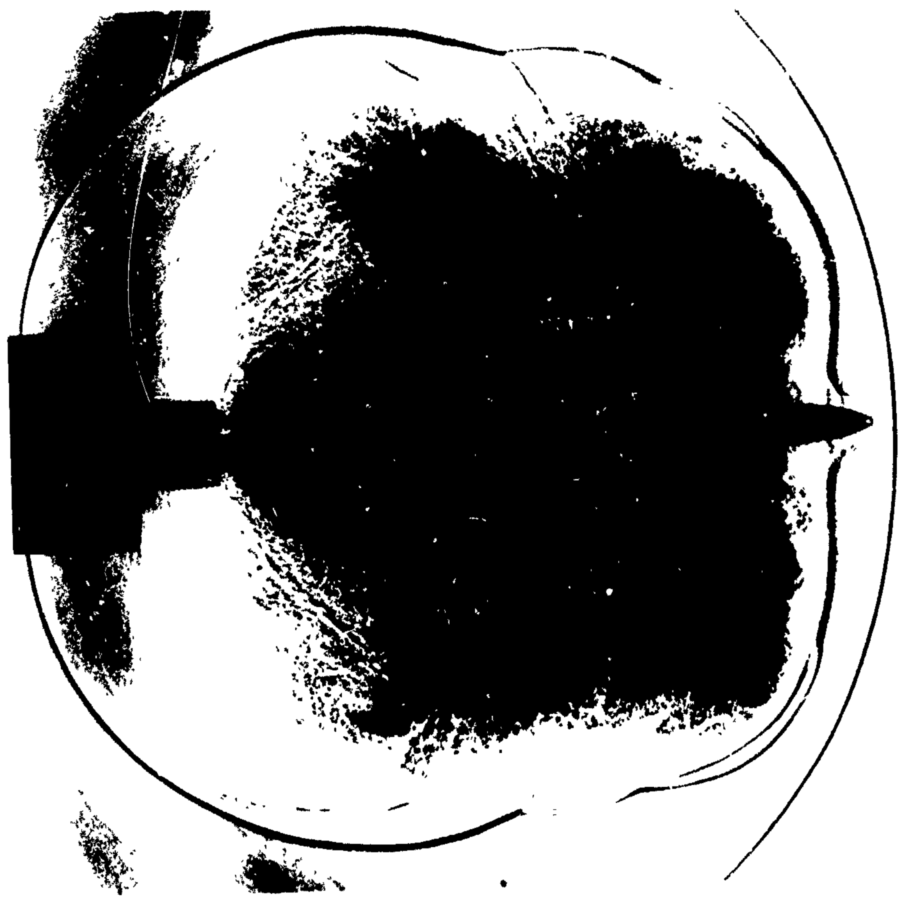
a. Precursor flow, t = -20μs

b. Propellant gas flow, t = 3μs



c. Propellant gas flow, t = 25μs

Figure 1. Spark shadowgraphs of muzzle flow from 5.56mm rifle



d. Propellant gas flow, t = 90μs

Figure 1. Spark shadowgraphs of muzzle flow from 5.56mm rifle

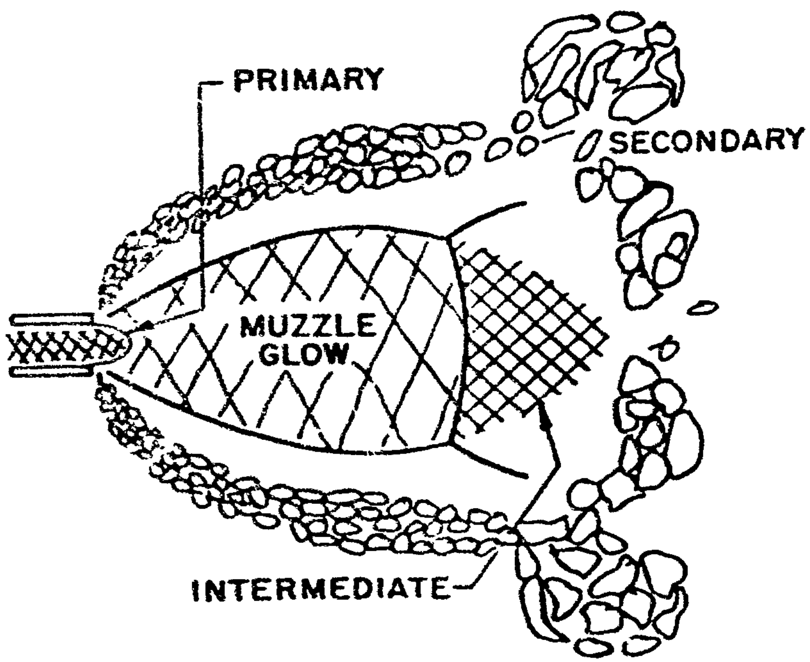
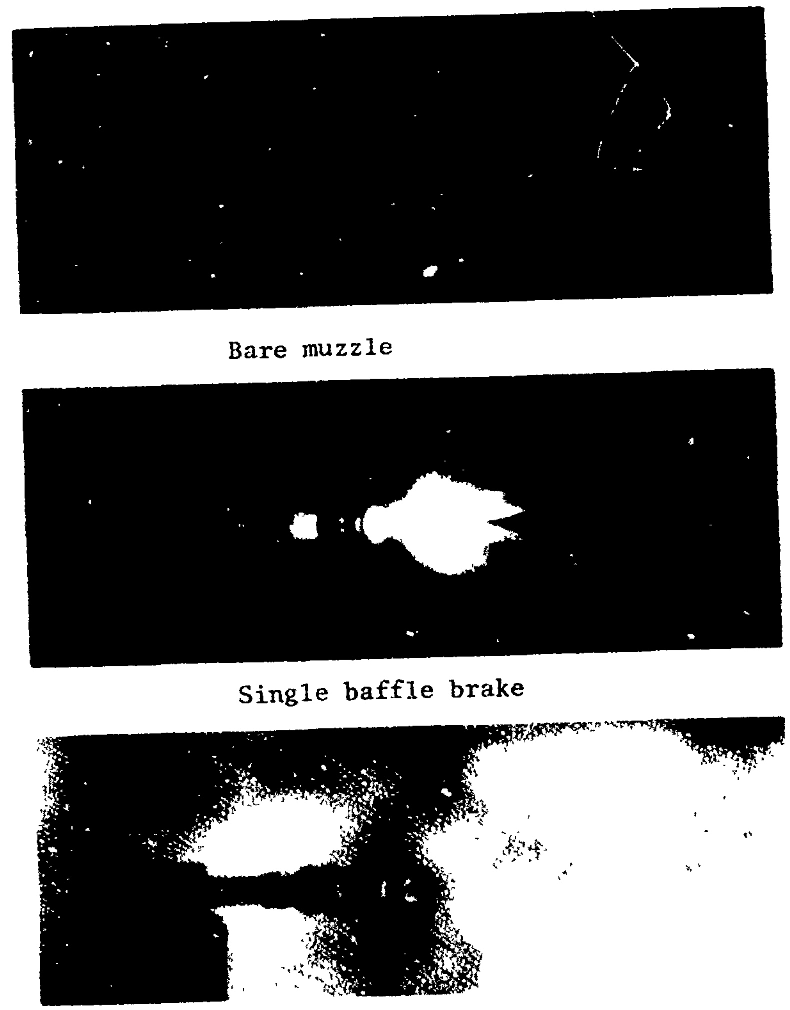


Figure 2. Schematic of muzzle flash



Bare muzzle

Single baffle brake

Double baffle brake

Figure 3. Muzzle flash from a 30mm cannon

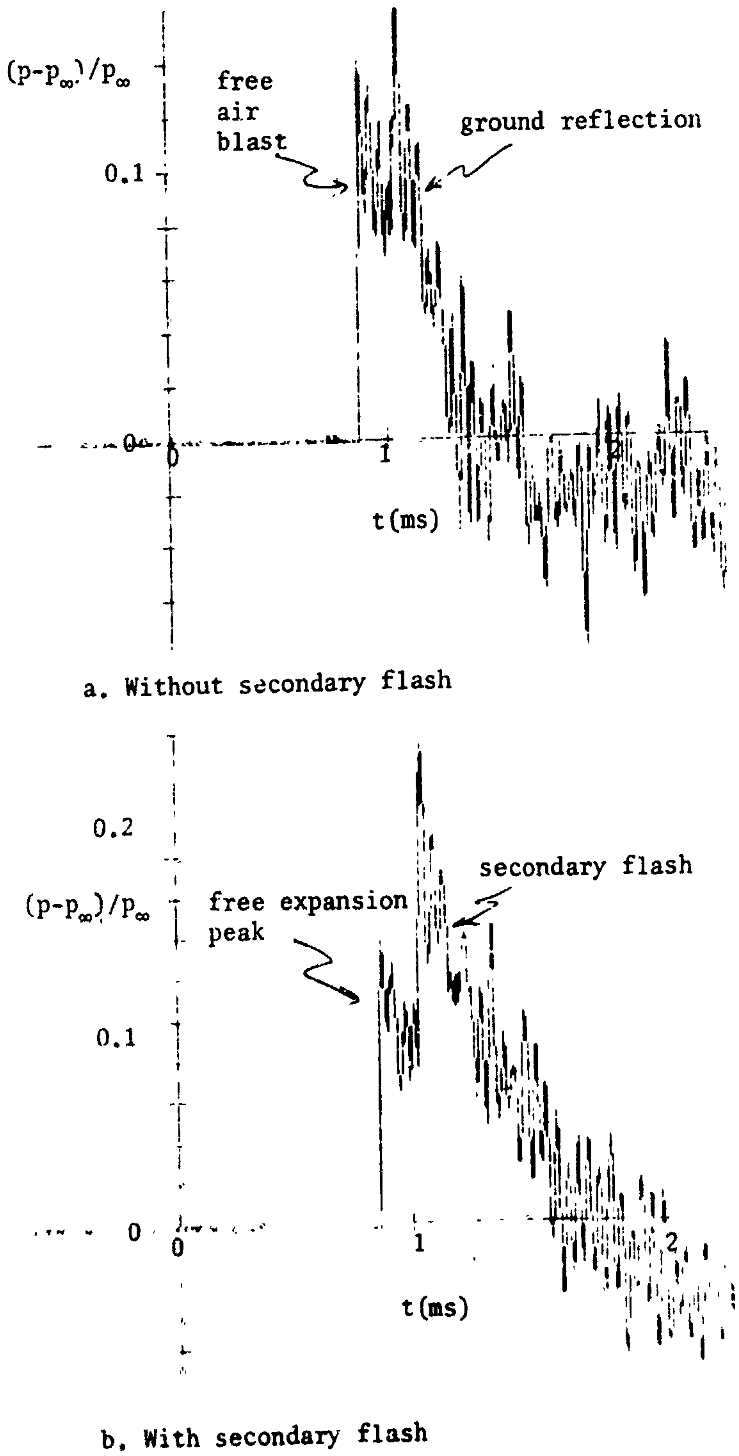


Figure 4. Free field blast overpressure 9.1m from the muzzle of a 155mm M109A1 Howitzer firing Zone 7 Charge.

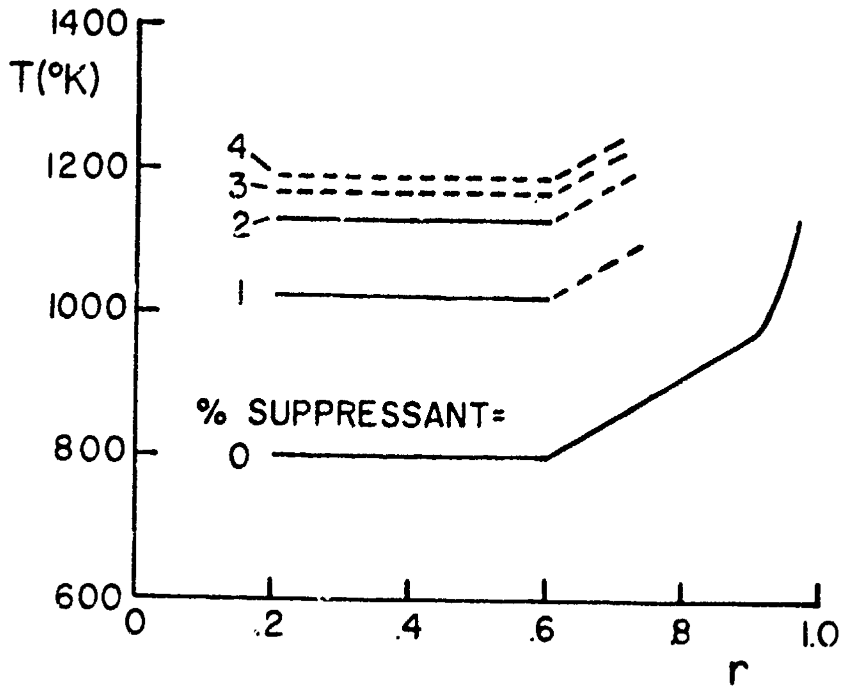


Figure 5. Carfagno ignition limits: r = 0, all propellant gas, and r = 1.0, all air (note: limits include 100°K safety factor of May and Einstein).

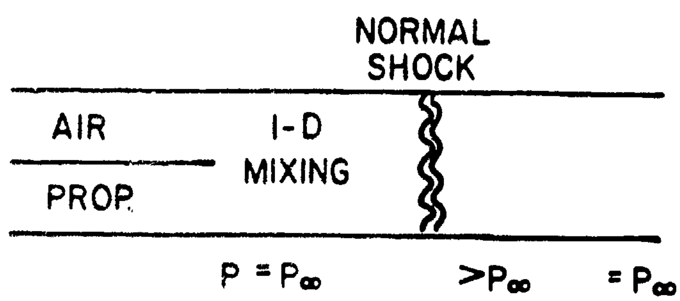


Figure 6. Carfagno flow model

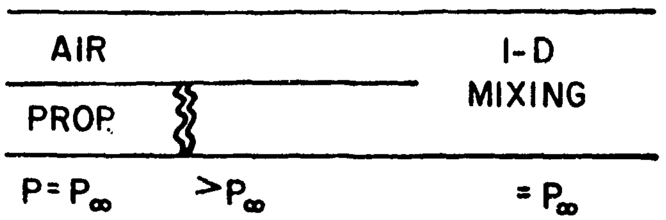


Figure 7. May and Einstein flow model

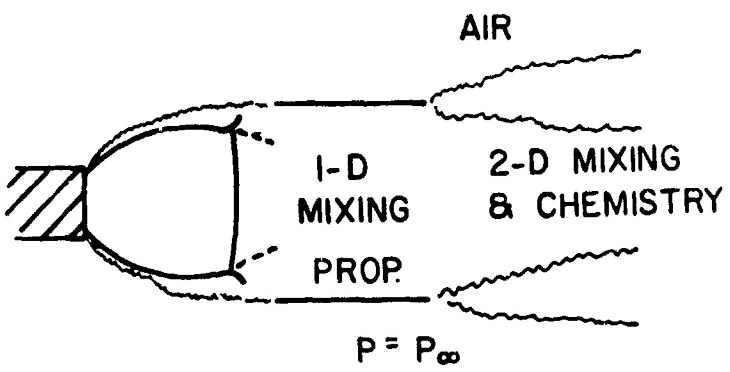


Figure 8. Yousefian flow model

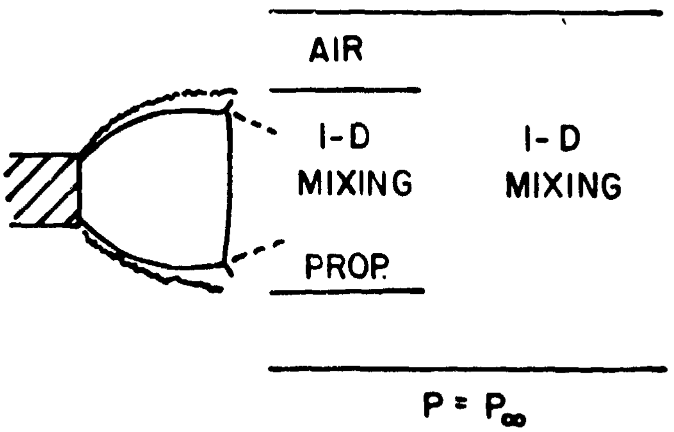


Figure 9. Present flow model

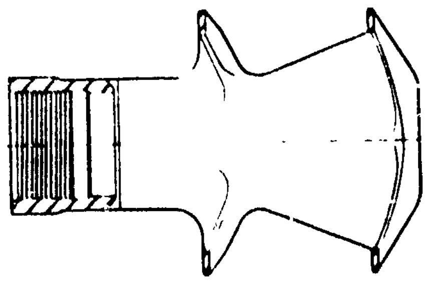


Figure 10. Double baffle brake for 155mm, M109 Howitzer

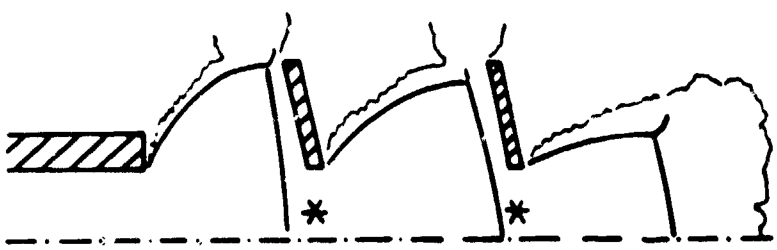


Figure 11. Schematic of flow internal to brake according to present model

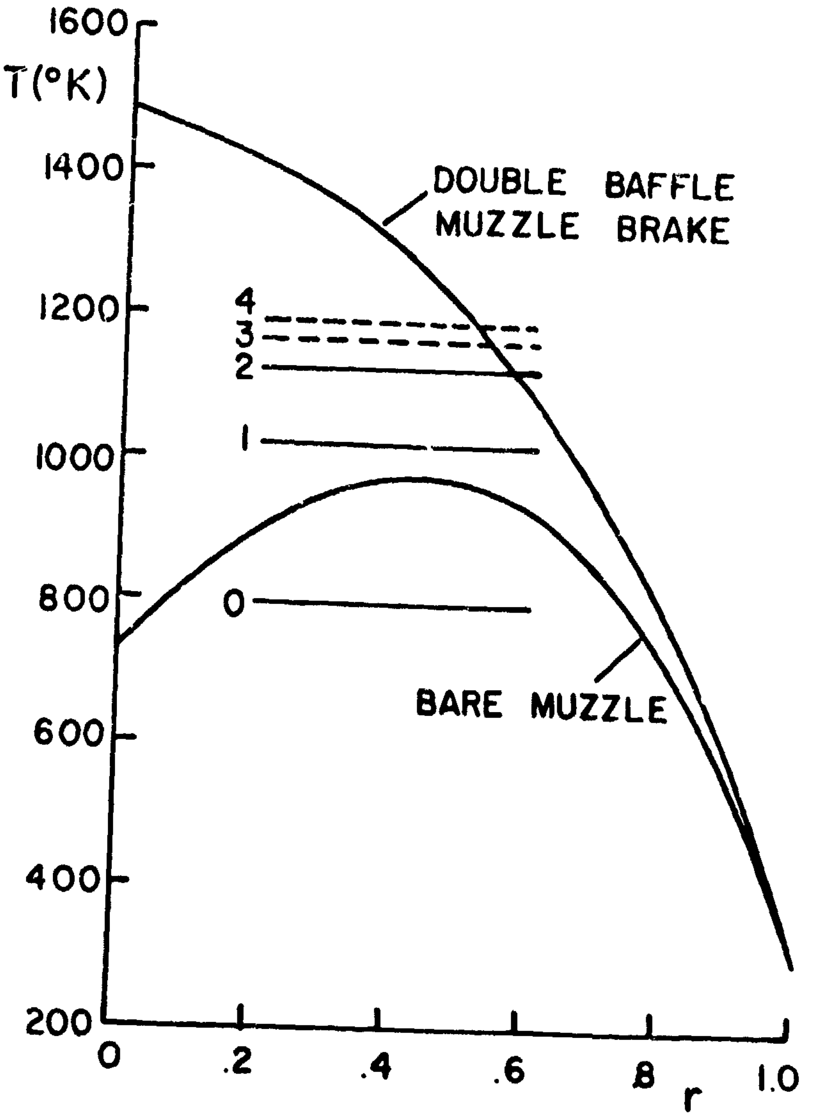


Figure 12. Comparison of mixture temperatures with and without brake for 155mm, M109A1 Howitzer firing Zone 8S Charge

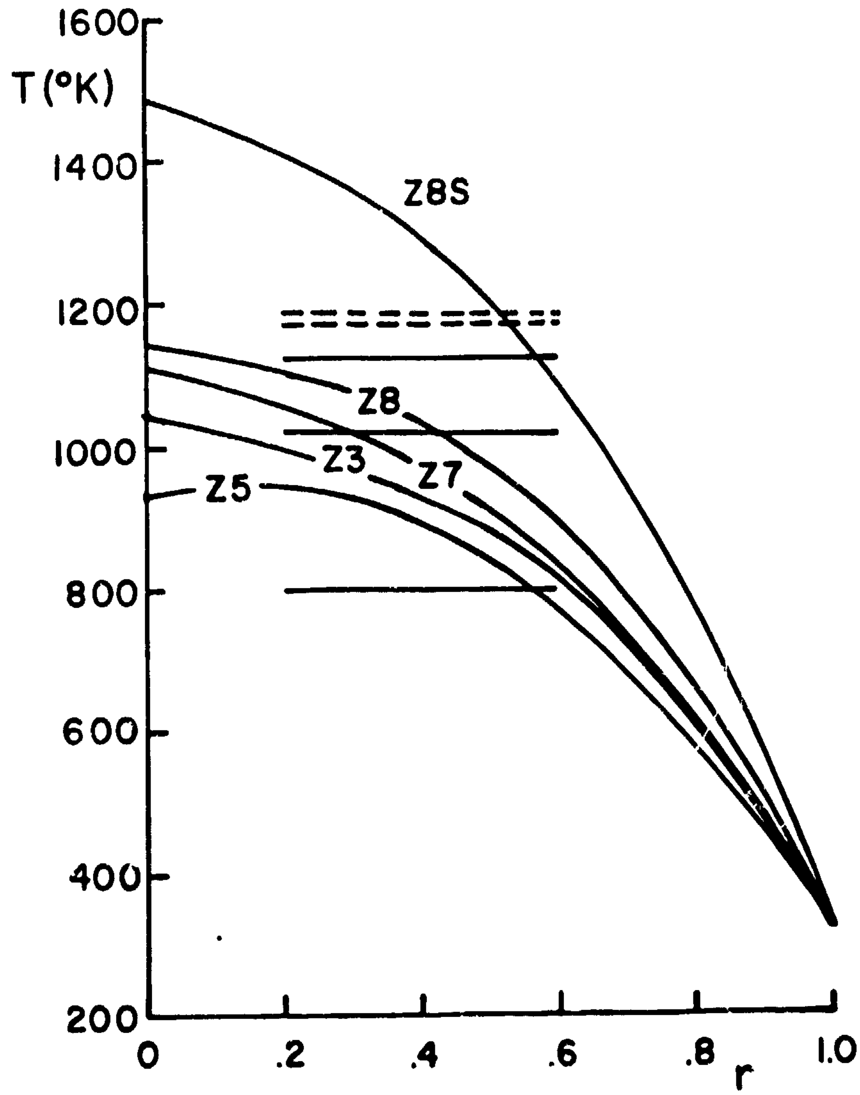


Figure 13. Mixture temperatures for various zones of fire of 155mm, M109A1 Howitzer equipped with muzzle brake

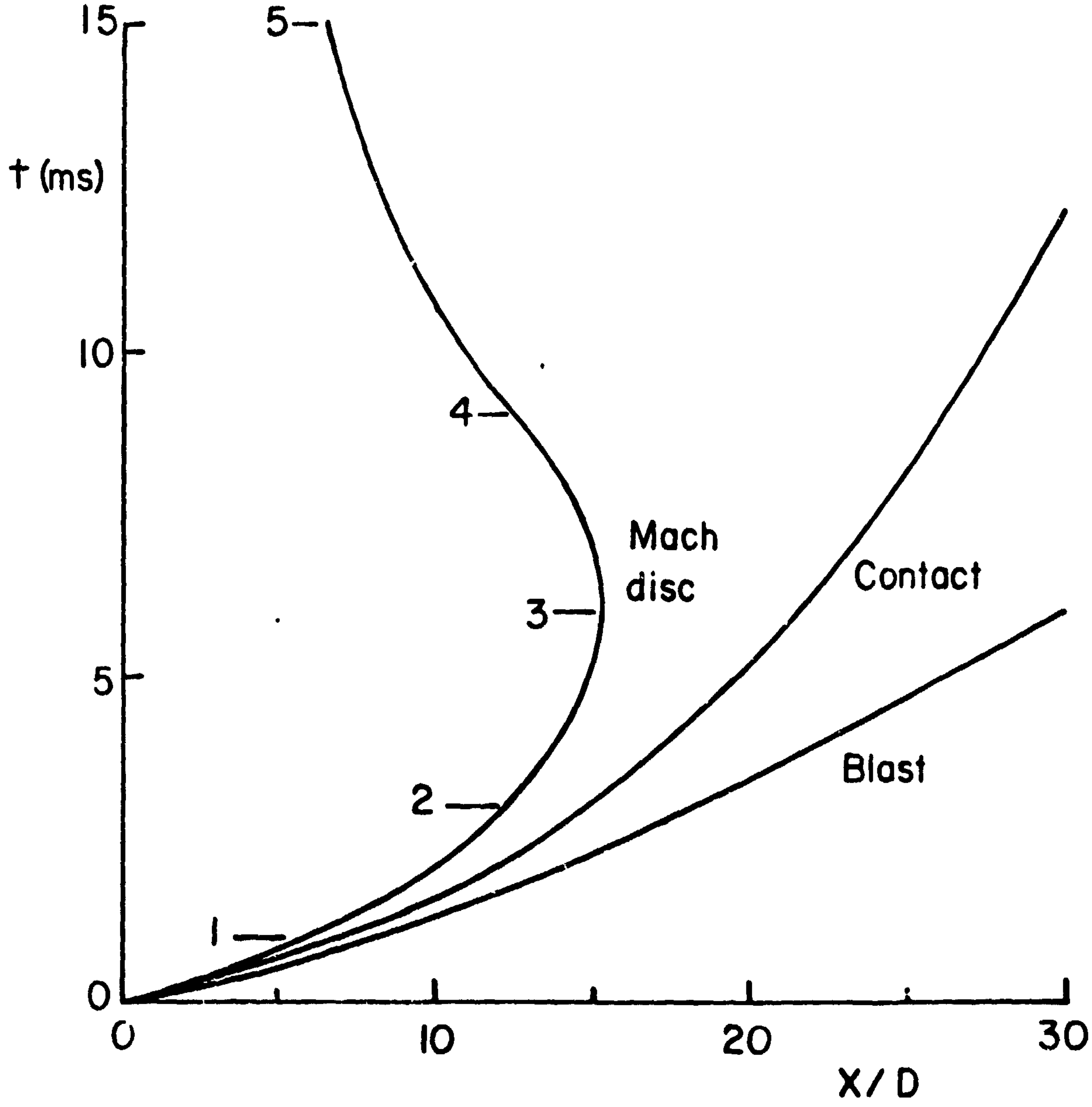
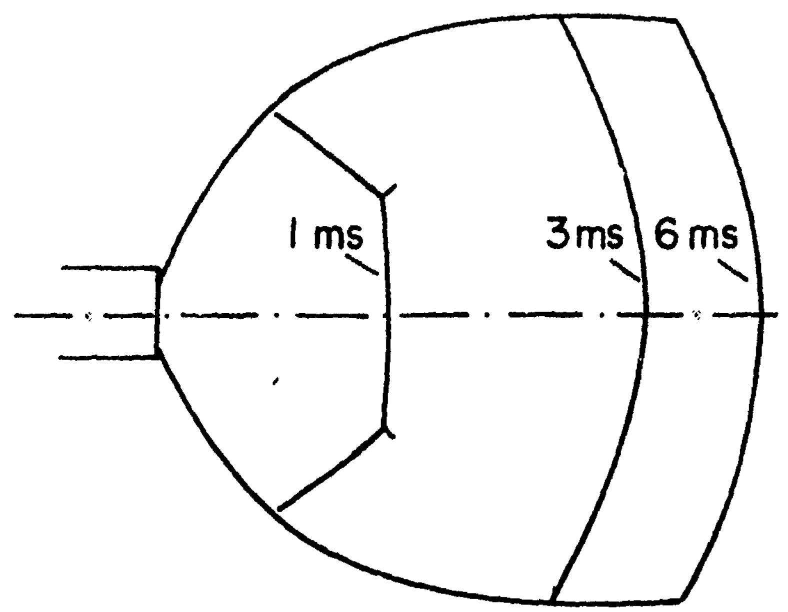
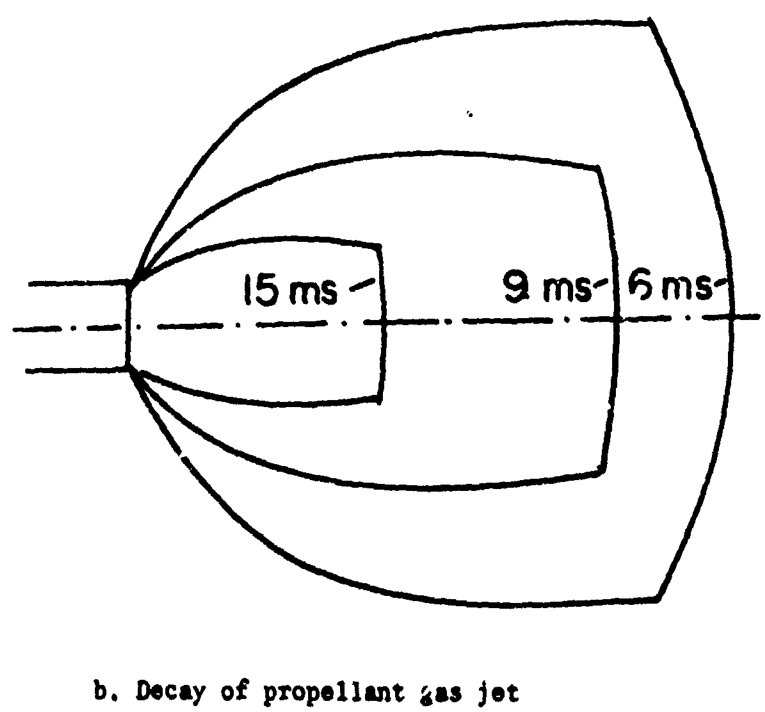


Figure 14. Muzzle discontinuity trajectories for 155mm, M109A1 Howitzer firing Zone 8S without muzzle device



a. Growth of propellant gas jet



b. Decay of propellant gas jet

Figure 15. Growth and decay of muzzle flow shock structure for 155mm, M109A1 Howitzer firing Zone 8S without muzzle brake

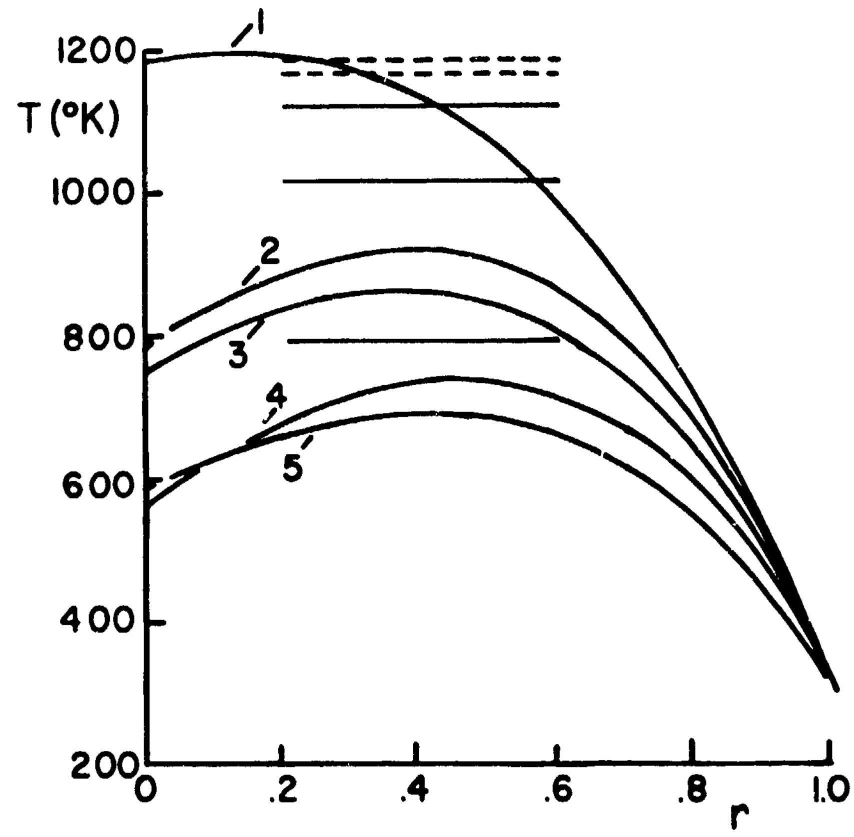


Figure 16. Mixture temperatures for selected, temporal exhaust plume properties of 155mm, M109A1 Howitzer firing Zone 8S without muzzle brake

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